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Interactive comment on “Impacts of cirrus clouds heterogeneities on TOA thermal infrared radiation” by T. Fauchez et al.

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First of all, we would like to thank the reviewer for its relevant comments and suggestions, which enhance the article quality. The typographical errors are now corrected and we added a figure concerning the heterogeneity effects as a function of the spatial resolution.

This is a very thorough study on the impact of cloud heterogeneity and associated 3-D radiative transfer effects on TOA IR brightness temperature observation. The topic is important and suitable for ACP. The manuscript is well prepared. There are a few typos in the manuscript, as pointed out by

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the other reviewer. The most important one is to change “Plan-Parallel” to “plane-Parallel”.

We changed it in the whole document.

I think this paper can be published after some minor revision. On the other hand, I do have several suggestions (listed below) and I think they may help the author to further improve the paper and attract more readers.

1) I'd like really like to see the authors to include $3.7 \mu\text{m}$ band in their analysis. I guess this paper is oriented to the IIR instrument, which does not have a $3.7 \mu\text{m}$ band. But the $3.7 \mu\text{m}$ band is commonly used band for cloud property retrievals, e.g., AVHRR, MODIS, VIIRS, SEVIRI, etc. During the day time $3.7 \mu\text{m}$ band radiance contains both solar reflection and thermal emission. The emission component has to be removed before $3.7 \mu\text{m}$ band can be used for cloud droplet size retrieval based on the Nakajima –King method. This so-called emission correction is usually done by relating $3.7 \mu\text{m}$ emission component with the $11 \mu\text{m}$ band observation. Cloud is assumed to be plane parallel in this step. An interesting and important question would be whether 3-D effect and PPA have different impact on 11 and $3.7 \mu\text{m}$ bands. The results in Figure 8 seem to suggest that the effect on $3.7 \mu\text{m}$ would be much larger than $11 \mu\text{m}$ band. If so, the results could have significant implications for many instruments using the $3.7 \mu\text{m}$ band. It is why I'd recommend the authors to include an analysis for the $3.7 \mu\text{m}$ band. As far as I know, there is only one previous study [Zhang and Platnick, 2011] (they had a very simple case study see their Figure 15) along this direction.

We agree that, as the $3.7 \mu\text{m}$ band contains information about the cloud particle size, it is important to study the heterogeneity effects in the solar and thermal part. However, our studies was really focused on the IIR instrument and $3.7 \mu\text{m}$ radiance simulations

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would take too many time to be included in this study. So, we prefer to keep it in mind for a future study.

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2) The current tests are done at the 1km resolution (i.e. resolution of IIR). Other instruments have different resolutions. I am wondering what is the scale dependence of the 3-D effect in the IR region. For example, consider two pixels with different size (say 1km vs. 5km), they have the same mean cloud optical thickness (COT) and COT standard deviation. The PPA effect would be the same for these two pixels, but how about the horizontal photon transfer effect? Since the authors used a fractal cloud generator, they are well positioned to answer this question. I will be very delighted to see some theoretical discussions to relate the PPA in the IR region with the, scale-invariant, fractal structure of cloud.

This comment is very relevant. Reviewer 2 also asked a question concerning the heterogeneity effects (mainly dominated by the PPA) as a function of the spatial resolution. We add thus in the paper two figures and paragraphs: one concerning the increase of the spatial resolution and PPA biases (see answer to question 6 of reviewer 2) and the other the scale of the horizontal photon transport (See Figure 9 in the revised version).

To comment Figure 9, we add:

"To evaluate the horizontal photon transport effects on TOA BT, we present in Fig 1 (9 in the revised paper) a step cirrus cloud. The optical thickness described at the scale of 100 m (τ_{100m}) is equal to 3.5 between 0 km and 2 km and to 0 after. "Thin cirrus" (solid lines) and "thick cirrus" (dashes lines) are two cirrus with the same optical thickness, the same top altitude but with different geometrical thickness

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(0.4 km and 2 km respectively). Curves represent the 3D brightness temperatures whereas the straight lines correspond to 1D brightness temperatures computed using IPA assumption. Logically, pixels with optical thickness equal to zero have large BT corresponding to clear sky atmosphere, while pixels with larger optical thickness have lower BT corresponding to top of the cirrus. Due to the stronger absorption at 12.05 μm , the BT differences between opaque pixels and clear sky pixels are greater for the band at 12.05 μm than at 8.65 μm . We note also that BT of "thick cirrus" are larger than those of "thin cirrus" because for the "thick cirrus", the energy emitted by the cloud base, which is closer to the surface is greater. Photon horizontal transport effects are visible near the optical thickness transition (between $\tau_{100\text{m}}=0$ and 3.5) where photons emitted from the surface cross over or are scattered in the cloud leading to an increase of the BT. This increase goes further in the case of the "thick cirrus" because, the mean extinction coefficient by cell is smaller and photons can spread further. For bands at 10.60 μm and at 12.05 μm , with higher absorption the pixels are impacted until 100 m for "thin cirrus" and 400-500 m for "thick cirrus". For 8.65 μm , cloud pixel far of 1km from the cloud edge can be impacted. We note that, based on the IIR accuracy of 1 K, photon horizontal transport effects become, in average, larger than this accuracy below a spatial resolution of 250 m."

3) A question related to the last point is whether the PPA bias could be corrected, at least at the nadir direction, based on the observed (biased) BT, on the basis of the scale invariant nature of cloud. In other words, if we know the statistics of cloud BT at larger scale, can we infer the sub-pixel level cloud inhomogeneity and furthermore correct the bias BT observation? To be clear, this is a question for the authors to consider. It's up to them to decide whether to explore in this direction.

The answer of this interesting problem needs a complete and future study not achiev-

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able for this paper. First, we need to be sure of the scale invariance properties of cirrus clouds; then, to study the relation between invariance of cloud properties and IR radiances. In the infrared range, we guess that as scattering and smoothing are weaker than in the visible range, this relation should be quite linear.

For check, we plot in Figure 2, for cirrus 2 and 8, the standard deviation of the optical thickness (σ_τ) and the standard deviation of the radiance (σ_{rad}) estimated from 100 m \times 100 m pixels at different scales for the band at 12.05 μm . We see that σ_τ and σ_{rad} increase together with the scale but σ_{rad} depends on the top altitude (Cirrus 2 and 8 have different cloud top altitude) and could also depends on cloud heterogeneity, optical thickness or microphysical properties. The cloud heterogeneity at large scale gives certainly information for the small scale but only in average. To correct each pixel individually, a sub-pixel information related to the cloud heterogeneity is needed.

4) As hinted by the last paragraph, there may be another paper coming to discuss the implications of the results in this paper for the IIR cirrus cloud retrievals. But the authors should keep in mind that many readers may not follow up. So I think it is a good idea to add some discussions at the end of the paper to talk about the potential implications for remote sensing. In particular, as shown in several recent studies [Marshak et al., 2006; Zhang et al., 2012], solar reflective method is subject to large errors caused by 3-D radiative transfer effects. Note that, the PPA bias can be reduced simply by reducing pixel size, while the 3-D radiative transfer effects are more difficult to control and may even become stronger when pixel size is reduced. The dominance of PPA in the IR BT seems to suggest great potential of IR method for retrieving the small-scale cloud structure, something I think should be discussed.

We are indeed finalizing another paper concerning the impact of cirrus heterogeneities
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on the retrieved optical properties (optical thickness and effective diameter). As you underline it, the thermal infrared has the advantage to have a slight photon transport effect, contrary to the visible range. The PPA bias could be decreased by reducing pixel size, but photon transport effects increase when pixel size is reduced even for IR BT. As we explained before and show now in Figure 9, the impact of photon transport becomes, in average, inferior to IIR accuracy (1 K) above the spatial resolution of 250 m. Therefore, assuming a 1 K radiometer accuracy, a spatial radiometer with a spatial resolution of 250 m x 250 m could retrieve cloud optical properties with low PPA bias and low 3D effects.

We add this paragraph in the summary:

“The slight photon transport effect in the thermal infrared, contrary to the visible range, leads to that heterogeneity effects are mainly due to the PPA bias. This bias should be easier to correct than 3D effects as it could be estimated with subpixel information or it could be decreased by reducing pixel size. However, photon transport effects increase when pixel size is reduced. For the IIR accuracy of 1 K, they become significant for spatial resolution below 250 m. Assuming a 1 K radiometer accuracy, a spatial radiometer with a spatial resolution of 250 m x 250 m could retrieve cloud optical properties with low PPA bias and low 3D effects.”

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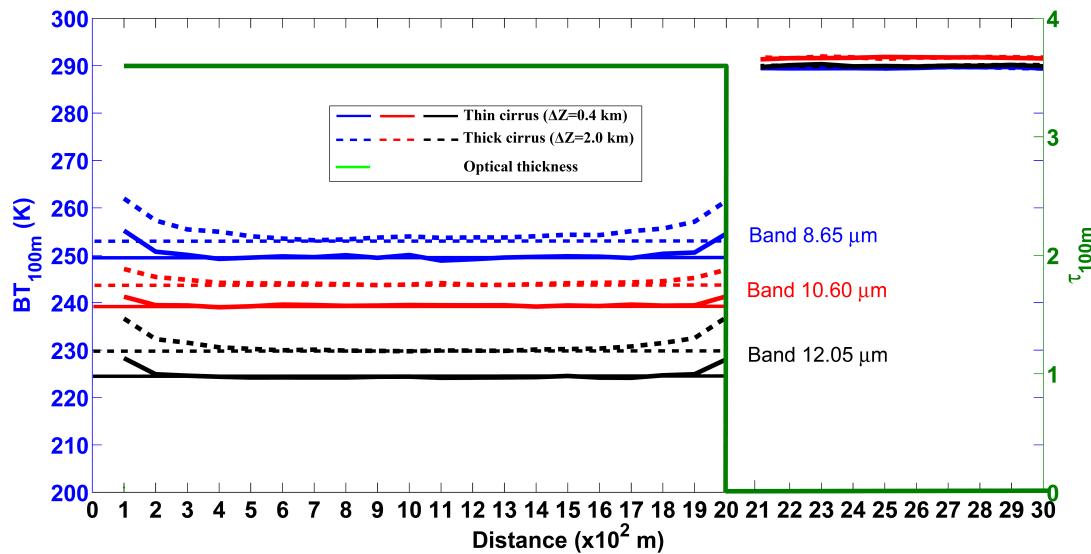
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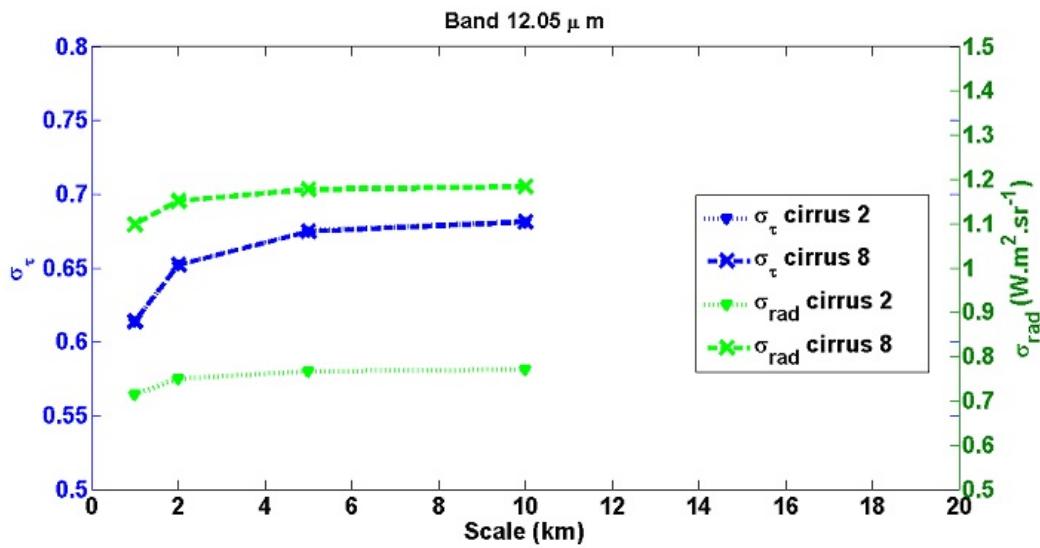
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